EARTHQUAKES & TECTONICS

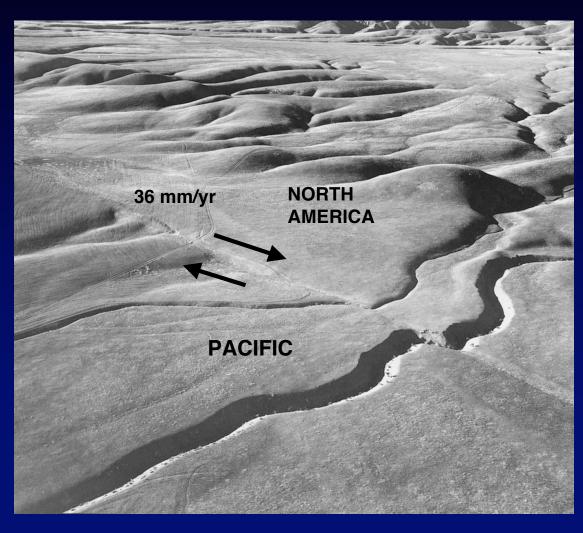## Seth Stein, Northwestern University

Locations map plate boundary zones & regions of intraplate deformation even in underwater or remote areas

Focal mechanisms show strain field

Slip & seismic history show deformation rate

Depths constrain thermo-mechanical structure of lithosphere

36 mm/yr

NORTH AMERICA

PACIFIC

San Andreas Fault, Carrizo Plain

STUDYING EARTHQUAKE FAULTING FROM THE SEISMIC WAVES IT GENERATES IS AN INVERSE PROBLEM

Arrival time of seismic waves at seismometers at different sites is first used to find the location and depth of earthquake

Amplitudes and shapes of radiated seismic waves used to study

- size of the earthquake
- geometry of the fault on which it occurred
- direction and amount of slip

Seismic waves give an excellent picture of the kinematics of faulting, needed to understand regional tectonics
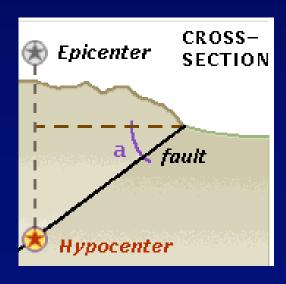
They contain much less information about the actual physics, or dynamics, of faulting

Accuracy (truth) depends primarily on velocity model

Precision (formal uncertainty) depends primarily on network geometry (close stations & eq within network help)
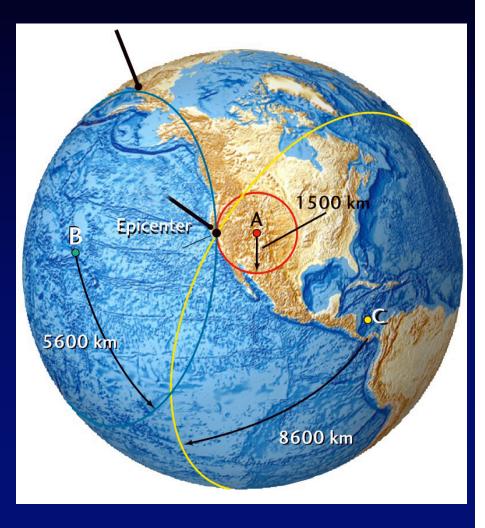
Locations can be accurate but imprecise or precise but inaccurate (line up nicely but displaced from fault)

Epicenters (surface positions) better determined than depths or hypocenters (3D positions) because seismometers only on surface
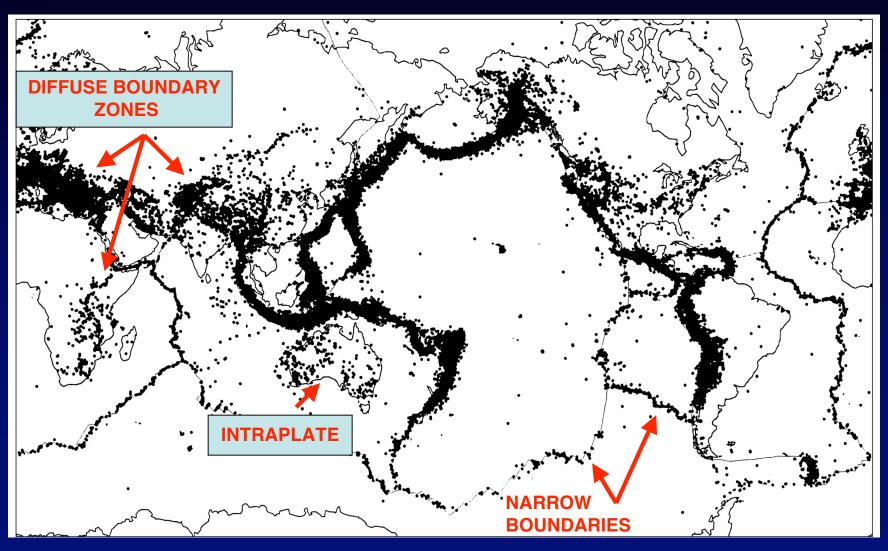
Least squares fit to travel times

CROSS-SECTION

Epicenter

a fault

Hypocenter

1500 km

Epicenter

B

A

C

5600 km

8600 km

Earthquake locations map narrow plate boundaries, broad plate boundary zones & regions of intraplate deformation even in underwater or remote areas
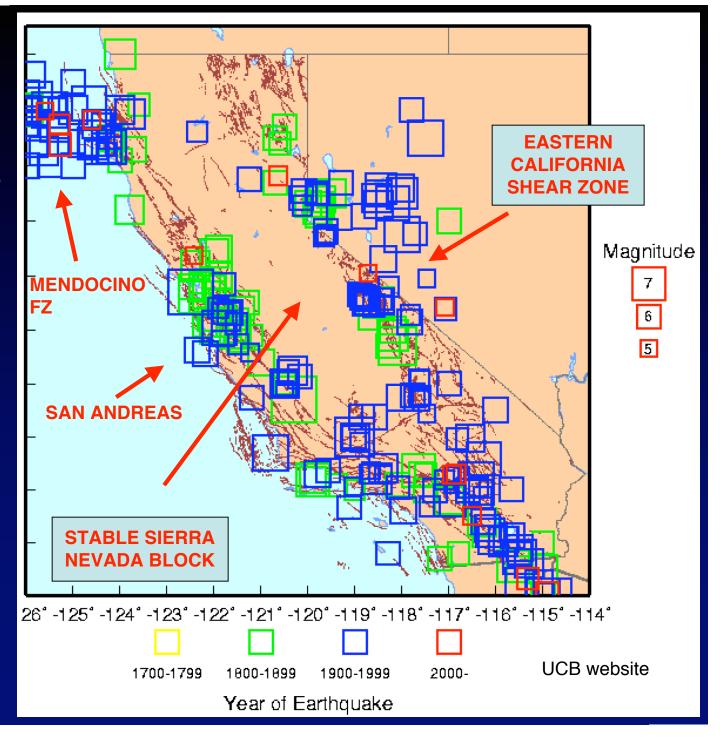

DIFFUSE BOUNDARY ZONES

INTRAPLATE

NARROW BOUNDARIES

EARTHQUAKES MAP FAULTS WELL AND DELINEATE STABLE BLOCKS

Sometimes, some places

How well depends on
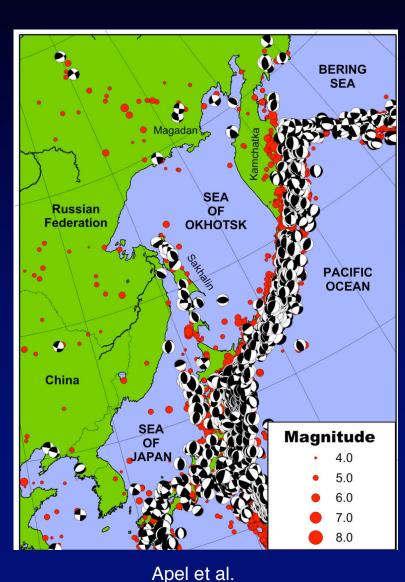
- magnitude threshold

- rate of motion

- duration of earthquake history

Some parts of SAF don't show up due presumably to short history

MENDOCINO FZ

SAN ANDREAS

STABLE SIERRA NEVADA BLOCK

EASTERN CALIFORNIA SHEAR ZONE

Magnitude

7

6

5

26° -125° -124° -123° -122° -121° -120° -119° -118° -117° -116° -115° -114°

1700-1799   1800-1899   1900-1999   2000-

Year of Earthquake

UCB website

SOME PLACES SEISMICITY INADEQUATE TO RESOLVE

Hard to tell if Okhotsk distinct from North America

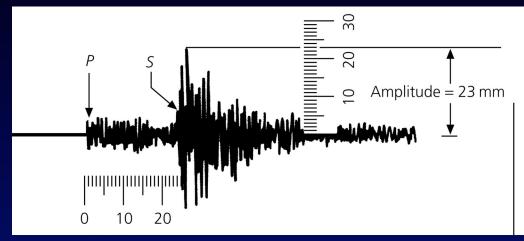Apel et al.

EARTHQUAKE MAGNITUDE

Earliest measure of earthquake size

Dimensionless number measured various ways, including

M_L local magnitude
m_b body wave magnitude
M_s surface wave magnitude
M_w moment magnitude

Easy to measure

Empirical - except for M_w, no direct tie to physics of faulting

General form of Magnitude scales:

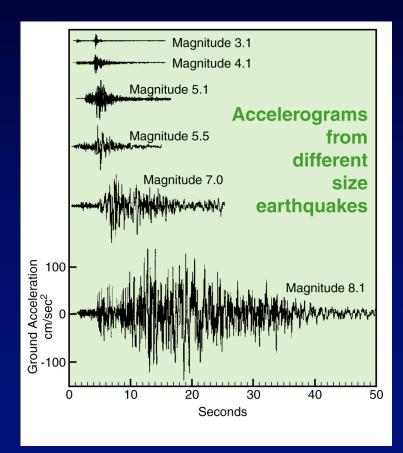$$M = \log(A/T) + F(h, \Delta) + C$$

A is the amplitude of the signal

T is its dominant period

F is a correction for the variation of amplitude with the earthquake's depth h and distance Δ from the seismometer

C is a regional scale factor

Note; not dimensionally correct

MAGNITUDE 8 IS MUCH BIGGER THAN MAGNITUDE 7

SEISMIC MOMENT Mo =
fault area * slip * rigidity
(dyn-cm)

MOMENT MAGNITUDE Mw =
log Mo /1.5 - 10.73

SUMATRA 2004

Mo 1×10^{30}
Mw 9.3
slip 11 m

NORTHRIDGE 1994

Mo 1×10^{26}
Mw 6.7
slip 1 m

LOMA PRIETA 1989

Mo 5.4×10^{26}
Mw 6.9
slip 2 m

SAN FRANCISCO 1906

Mo 5×10^{27}
Mw 7.8
slip 4 m

"the big one"

150 km

Magnitude 3.1
Magnitude 4.1
Magnitude 5.1
Magnitude 5.5
Magnitude 7.0
Magnitude 8.1

Accelerograms from different size earthquakes

Ground Acceleration cm/sec^2

100

0

-100

0   10   20   30   40   50

Seconds

University of Nevada
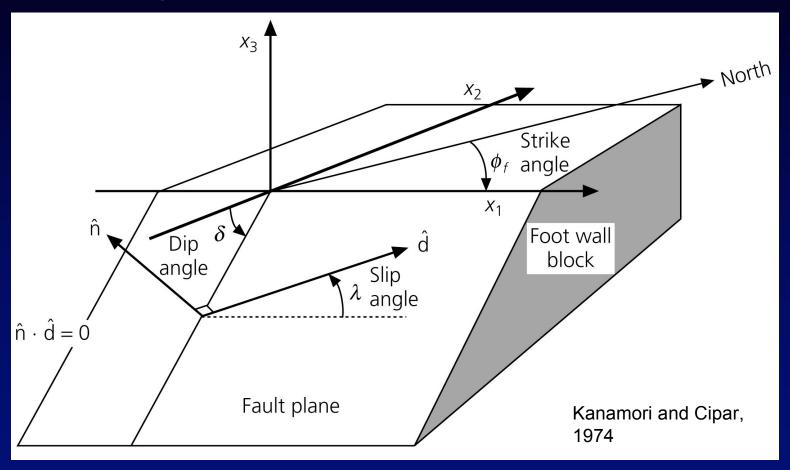
FAULT GEOMETRY REPRESENTED BY EITHER
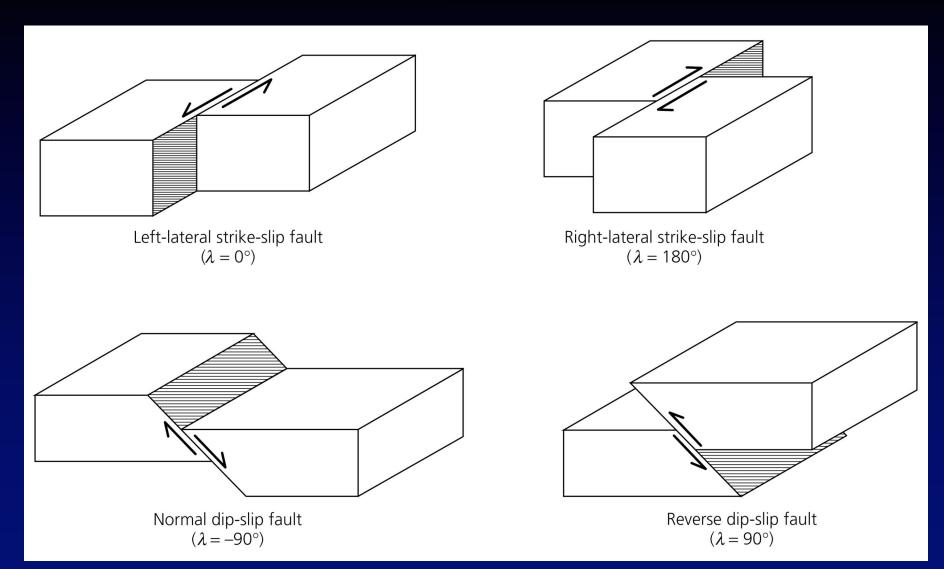
Three angles: strike ϕ, dip δ, slip λ, or

Two orthogonal vectors: fault normal n and slip vector d

Kanamori and Cipar, 1974

Treating fault as rectangular, the dimension along strike is the fault length and dimension in the dip direction is the fault width.

SLIP ANGLE λ CHARACTERIZES FAULT TYPE

Left-lateral strike-slip fault
($\lambda = 0°$)

Right-lateral strike-slip fault
($\lambda = 180°$)

Normal dip-slip fault
($\lambda = -90°$)

Reverse dip-slip fault
($\lambda = 90°$)

Most earthquakes consist of some combination of these motions,
and have slip angles between these values

ACTUAL EARTHQUAKE FAULT GEOMETRIES CAN BE MUCH MORE COMPLICATED THAN A RECTANGLE

Fault may curve, and require 3D-description.

Rupture can consist of sub-events on different parts of the fault with different orientations.

Can be treated as superposition of simple events.

First, the fault model setup

1992 Landers, California Mw 7.3

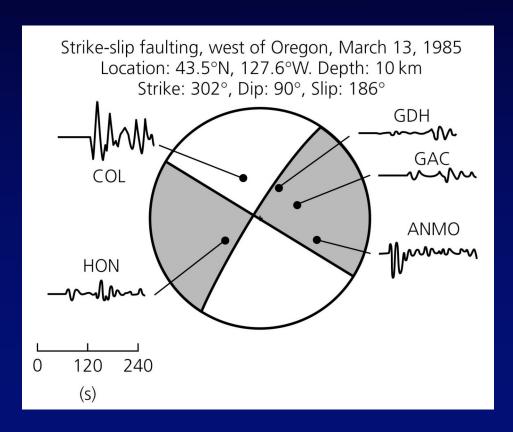SCEC Website

HOW FAST DOES RUPTURE MOVE?

Seismograms recorded at various distances and azimuths used to study geometry of faulting during an earthquake, known as the focal mechanism.
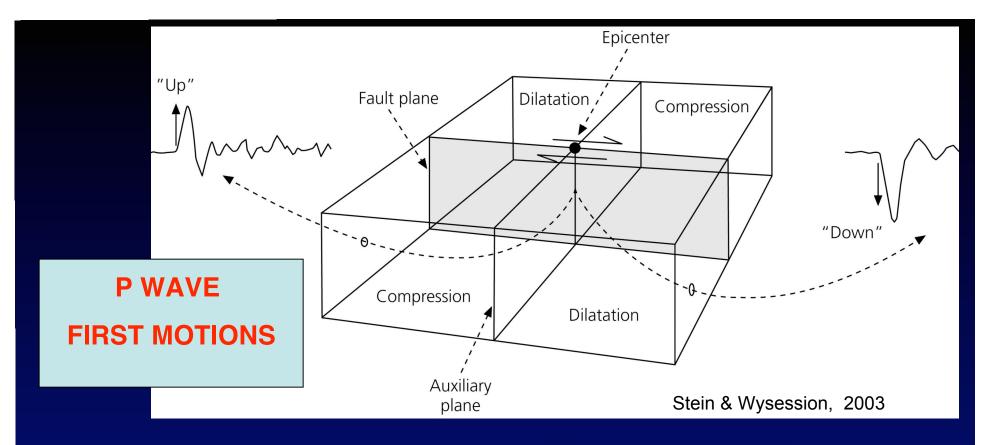
Use fact that the pattern of radiated seismic waves depends on fault geometry.

Simplest method relies on the first motion, or polarity, of body waves.

More sophisticated techniques use waveforms of body and surface waves.
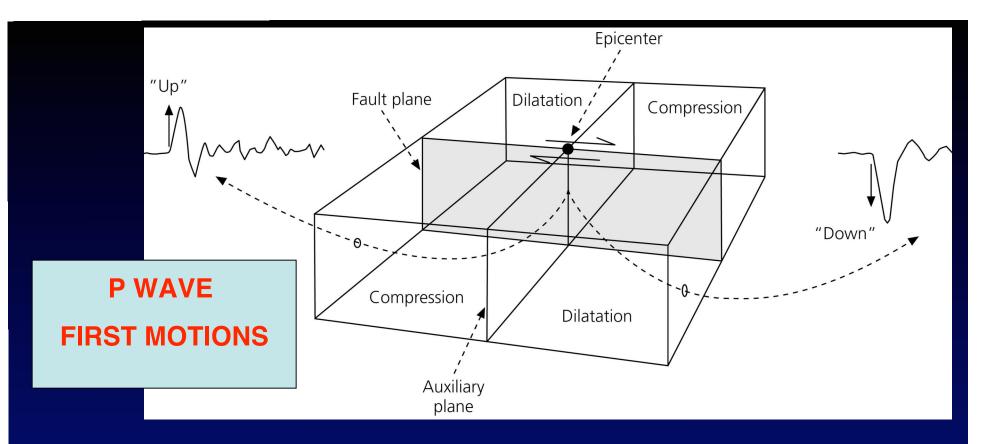
EARTHQUAKE FOCAL MECHANISM STUDY

Strike-slip faulting, west of Oregon, March 13, 1985
Location: 43.5°N, 127.6°W. Depth: 10 km
Strike: 302°, Dip: 90°, Slip: 186°

COL
GDH
GAC
ANMO
HON

0   120   240
(s)

Stein & Wysession, 2003

P WAVE

FIRST MOTIONS

Polarity of first P-wave arrival varies between seismic stations in different directions.

First motion is compression for stations located such that material near the fault moves ``toward'' the station, or dilatation, where motion is ``away from'' the station.

When a P wave arrives at a seismometer from below, a vertical component seismogram records up or down first motion, corresponding to either compression or dilatation.

P WAVE

FIRST MOTIONS

First motions define four quadrants; two compressional and two dilatational.

Quadrants separated by nodal planes: the fault plane and auxiliary plane perpendicular to it.
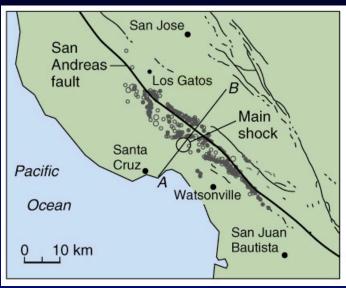
From the nodal planes fault geometry is known.

Because motions from slip on the actual fault plane and from slip on the auxiliary plane would be the same, first motions alone cannot resolve which is the actual fault plane.
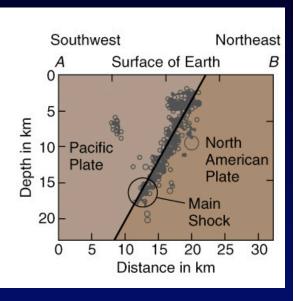
Sometimes geologic or geodetic information, such as **trend of a known fault** or observations of ground motion, indicates the fault plane.

Often, **aftershocks** following the earthquake occur on and thus delineate the fault plane.

If the earthquake is large enough, the finite time required for slip to progress along the fault causes variations in the waveforms observed at different directions from the fault, so these **directivity** effects can be used to infer the fault plane.

FIRST MOTIONS ALONE CANNOT RESOLVE WHICH PLANE IS THE ACTUAL FAULT PLANE
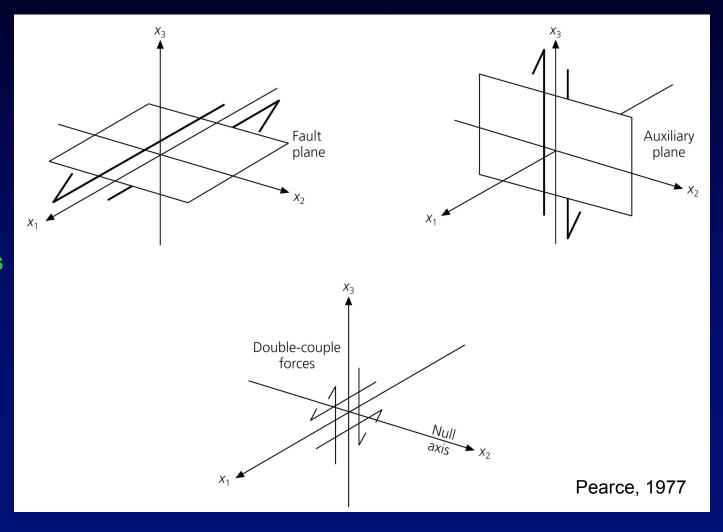
1989 Loma Prieta, California Ms 7.1

RADIATED SEISMIC WAVES FROM FAULT DESCRIBED BY FORCE DOUBLE COUPLE

Radiation due to motion on the fault plane is what would occur for a pair of force couples, pairs of forces with opposite direction a small distance apart.

One couple is oriented in the slip direction with forces on opposite sides of the fault plane, other couple oriented in corresponding direction on opposite sides of the auxiliary plane.

Pearce, 1977

P-wave radiation amplitude patterns:

$$u_r = \frac{1}{4\pi\rho\alpha^3 r}\; \dot{M}(t - r/\alpha)\, \sin 2\theta\, \cos\phi.$$

$\dfrac{1}{4\pi\rho\alpha^3 r}\;=\;$ amplitude term, with geometric spreading

$\sin 2\theta\, \cos\phi\;=\;$ *P*-wave radiation pattern (4-lobed)
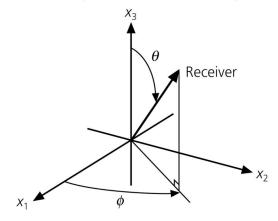
$\dot{M}(t - r/\alpha)\;=\;$ source time function

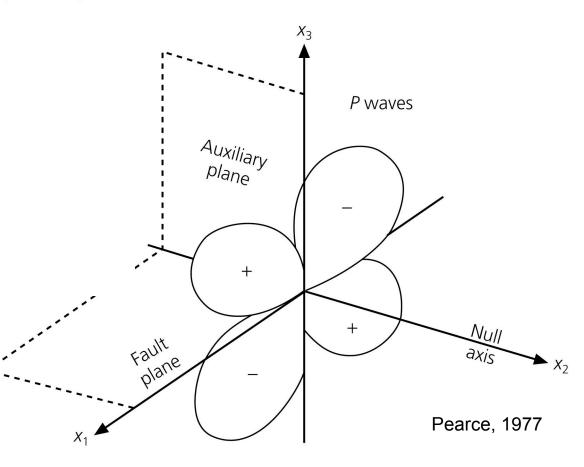$\dot{M}$ is the time derivative of the seismic moment function,

$$M(t) = \mu D(t) S(t)$$

$D(t) =$ slip history
$S(t) =$ fault area history

4-LOBED P WAVE RADIATION PATTERN

Pearce, 1977

SEISMIC MOMENT SCALES THE WAVEFORMS

Gives insight into the amount of slip if we know the fault area from aftershocks, geodesy, or other information

Mo in N-m or dyn-cm

N-m = 10^7 dyn-cm

Earthquake size is given by the scalar seismic moment,

$$M_0 = \mu \bar{D} S$$

$\bar{D}$ = average slip (dislocation)

S = "average" fault area

Seismic moment is often given as
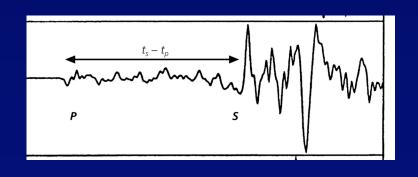
$$M(t) = M_0 x(t)$$

$x(t)$ = source time function.

SHEAR WAVE RADIATION PATTERN

S-wave radiation amplitude patterns:

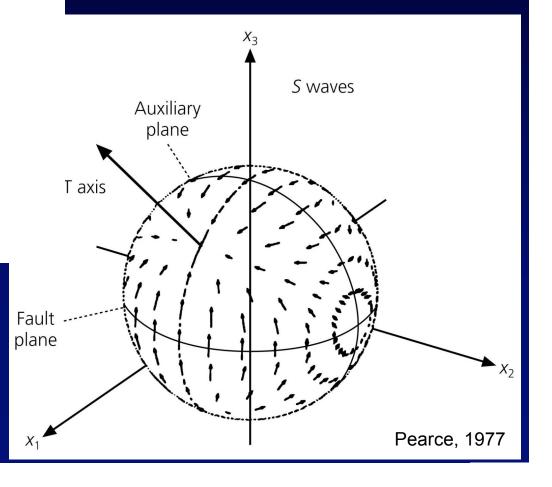$$u_\theta = \frac{1}{4\pi\rho\beta^3 r}\, \dot{M}(t - r/\beta)\cos 2\theta \cos\phi$$

$$u_\phi = \frac{1}{4\pi\rho\beta^3 r}\, \dot{M}(t - r/\beta)\,(-\cos\theta\sin\phi)$$

Why are S waves usually larger than P waves?

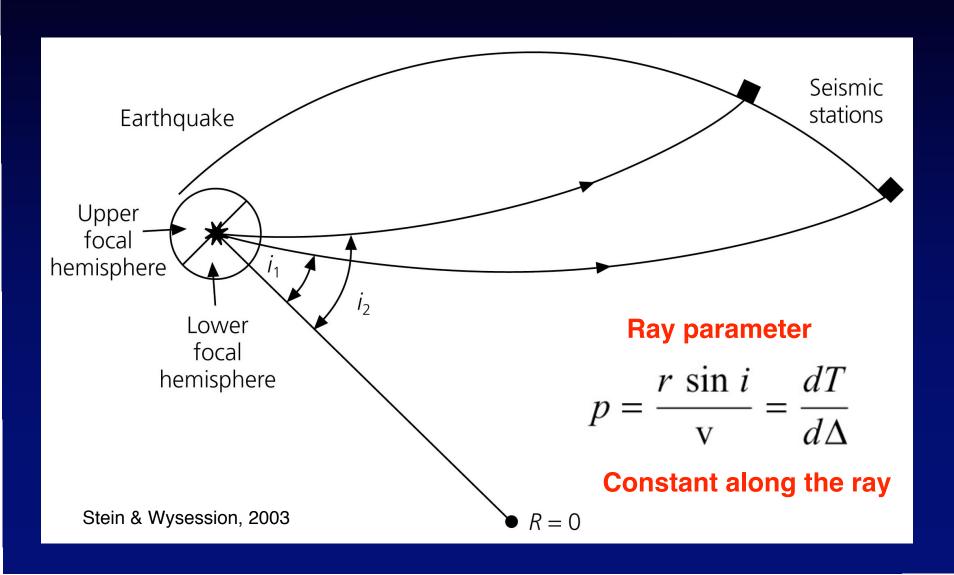These equations predict an average ratio of about α^3/β^3 or about 5.

$t_s - t_p$

P   S

x_3

S waves

Auxiliary plane

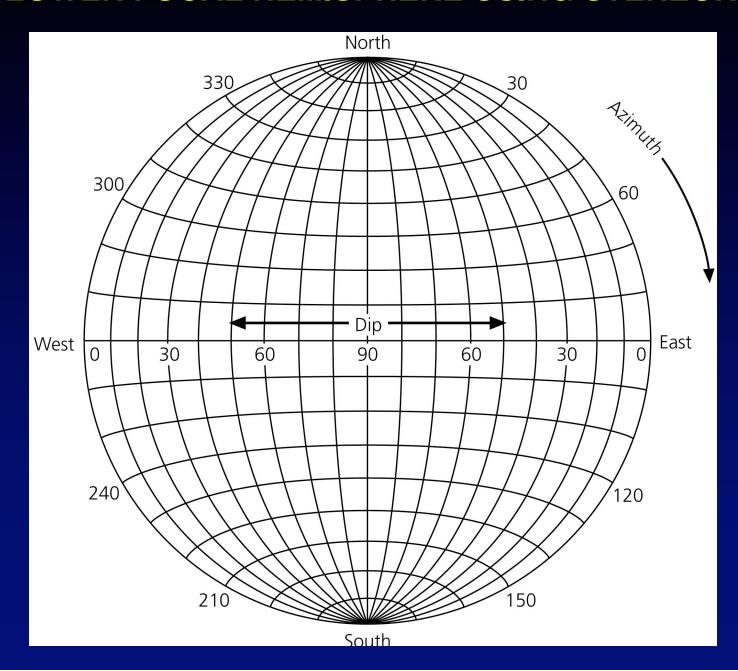T axis

Fault plane

x_1

x_2

Pearce, 1977

SEISMIC RAYS BEND DUE TO VELOCITY INCREASING WITH DEPTH

Snell's law for ray path in sphere places arrivals recorded at distant stations where they would be on hemisphere just below earthquake
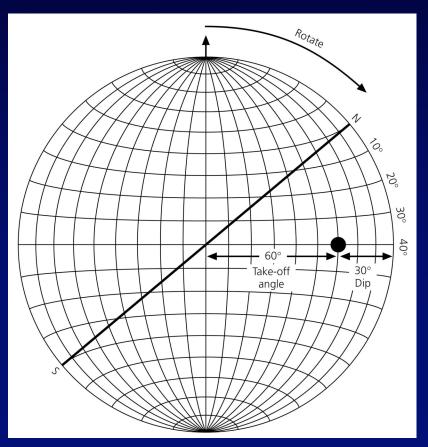
Earthquake

Upper focal hemisphere

Lower focal hemisphere

i_1

i_2

Seismic stations

Ray parameter

$$p = \frac{r \sin i}{v} = \frac{dT}{d\Delta}$$

Constant along the ray

Stein & Wysession, 2003

$R = 0$

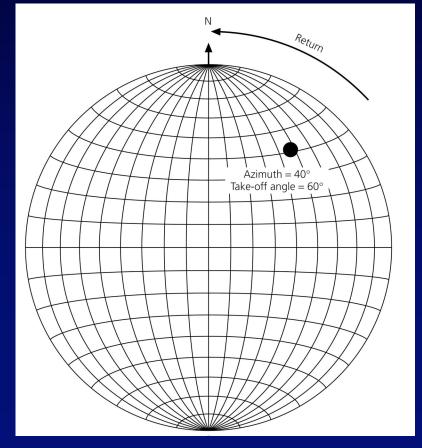# PLOT LOWER FOCAL HEMISPHERE USING STEREONET

Stein &
Wysession,
2003

PLOT FIRST MOTIONS

Find polarities of the first arrivals at seismic stations.

Station corresponds to a point on the focal sphere with the same azimuth and an incidence angle corresponding to the ray that emerged there.

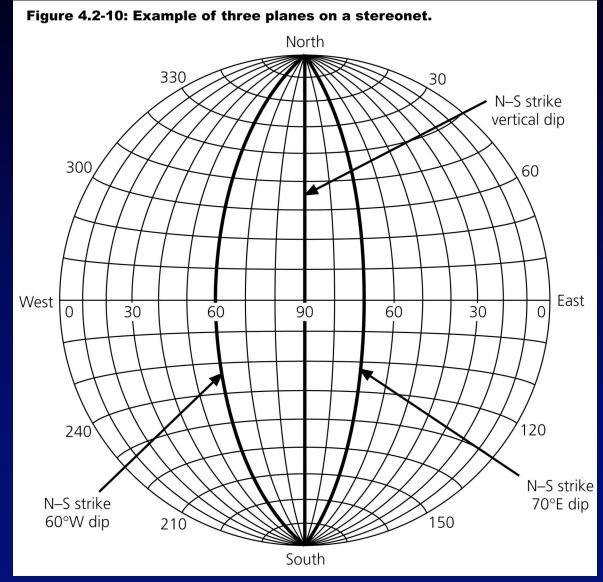Plot stations on the stereonet, and mark whether the first motion is dilatation or compression

PLOT NODAL PLANES

Find nodal planes that separate compressions from the dilatations.

Ensure the two planes are orthogonal, with each one passing through the pole to the other.

If distribution of stations on the focal sphere is adequate, we can find the nodal planes, which are the fault plane and the auxiliary plane.

Figure 4.2-10: Example of three planes on a stereonet.

Figure 4.2-11: Example of plotting a plane on a stereonet.

First draw a plane with a dip of 60°E and a strike of 0°.
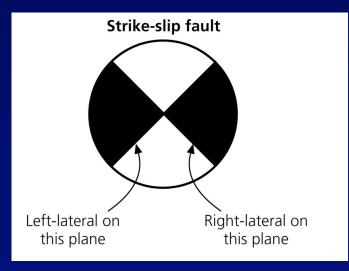
Then rotate 45°.

Strike N45°E dip 60°E

Stein & Wysession, 2003

Figure 4.2-12: Example of plotting perpendicular planes on a stereonet.
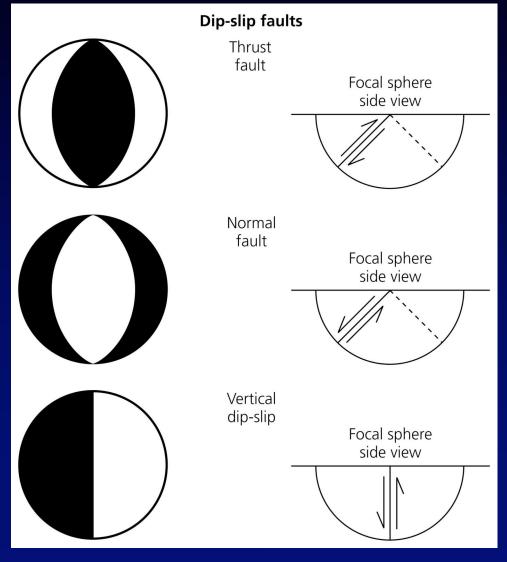
Although the focal mechanisms look different, they reflect the same four-lobed P-wave radiation pattern

However, because the fault plane and slip direction are oriented differently relative to the earth's surface, the projections of the radiation pattern lobes on the lower focal hemisphere differ

To see this, mark the P wave quadrants on a ball and rotate it.

FOCAL MECHANISMS FOR BASIC FAULTS

Strike-slip fault

Left-lateral on this plane

Right-lateral on this plane

Dip-slip faults

Thrust fault

Focal sphere side view

Normal fault

Focal sphere side view

Vertical dip-slip

Focal sphere side view

Stein & Wysession, 2003

FOCAL MECHANISMS FOR DIFFERENT FAULTS

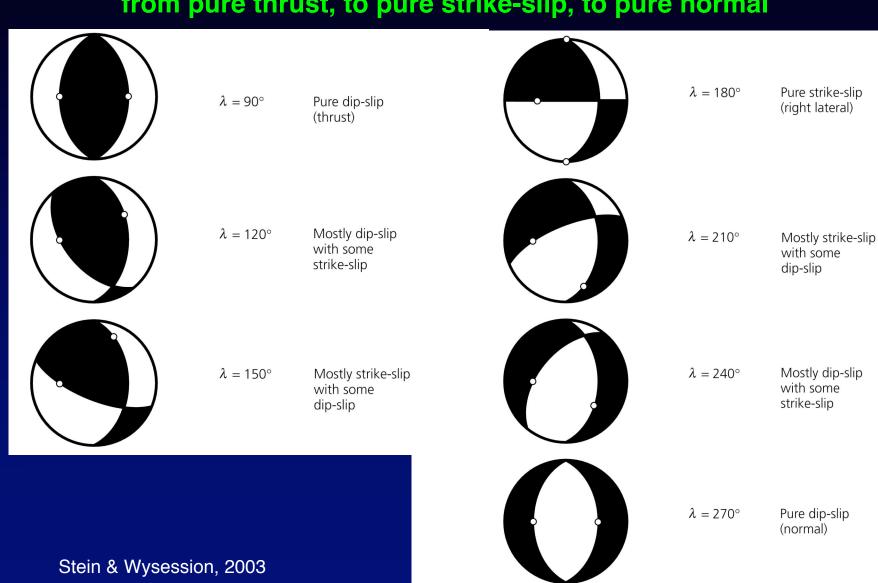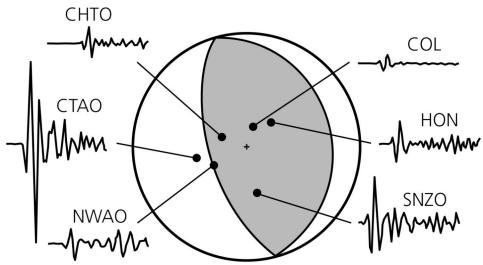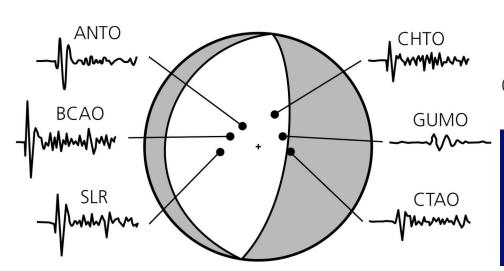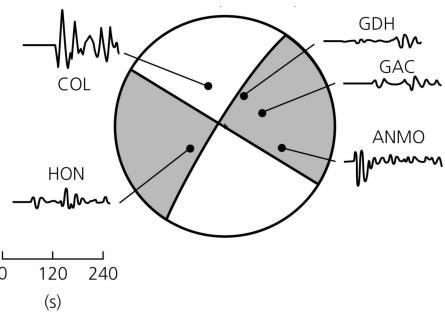## All have same N-S striking plane, but with slip angles varying from pure thrust, to pure strike-slip, to pure normal

$\lambda = 90°$ — Pure dip-slip (thrust)

$\lambda = 120°$ — Mostly dip-slip with some strike-slip

$\lambda = 150°$ — Mostly strike-slip with some dip-slip

$\lambda = 180°$ — Pure strike-slip (right lateral)

$\lambda = 210°$ — Mostly strike-slip with some dip-slip

$\lambda = 240°$ — Mostly dip-slip with some strike-slip

$\lambda = 270°$ — Pure dip-slip (normal)

Stein & Wysession, 2003

Figure 4.2-17: Examples of focal mechanisms and first motions.
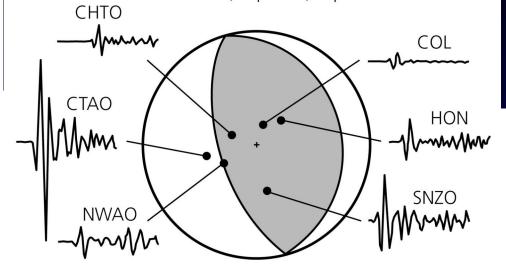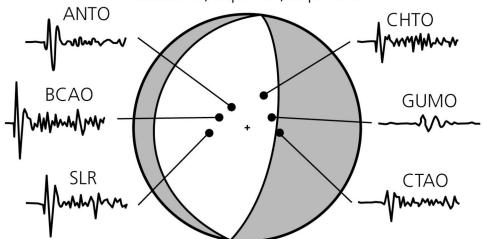
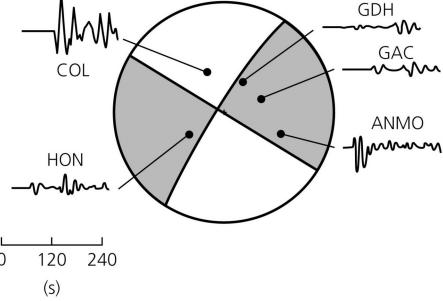**Figure 4.2-17: Examples of focal mechanisms and first motions.**

Thrust faulting, Vanuatu Islands, July 3, 1985
Location: 17.2°S, 167.8°E. Depth: 30 km
Strike: 352°, Dip: 26°, Slip: 97°

CHTO
COL
CTAO
HON
NWAO
SNZO

Strike-slip faulting, west of Oregon, March 13, 1985
Location: 43.5°N, 127.6°W. Depth: 10 km
Strike: 302°, Dip: 90°, Slip: 186°

GDH
GAC
COL
ANMO
HON

0   120   240
(s)

Normal faulting, mid-Indian rise, May 16, 1985
Location: 29.1°S, 77.7°E. Depth: 10 km
Strike: 8°, Dip: 70°, Slip: 270°

ANTO
CHTO
BCAO
GUMO
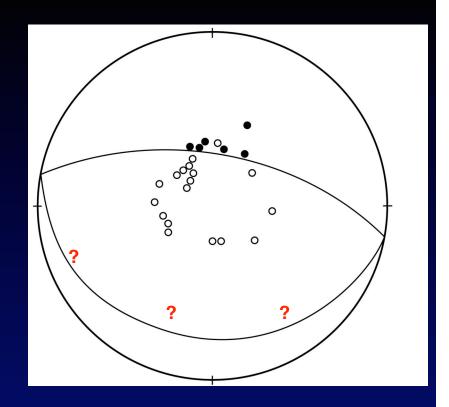SLR
CTAO

Stein & Wysession, 2003

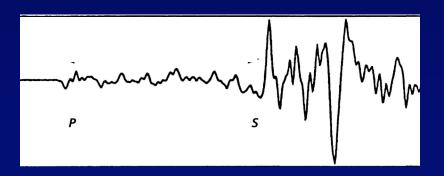## SOMETIMES FIRST MOTIONS DON'T CONSTRAIN FOCAL MECHANISM

Especially likely when

- Few nearby stations, as in the oceans, so arrivals are near center of focal sphere

- Mechanism has significant dip-slip components, so planes don't cross near center of focal sphere

Additional information is obtained by comparing the observed body and surface waves to theoretical, or synthetic waveforms computed for various source parameters, and finding a model that best fits the data, either by forward modeling or inversion.

Waveform analysis also gives information about earthquake depths and rupture processes that can't be extracted from first motions.
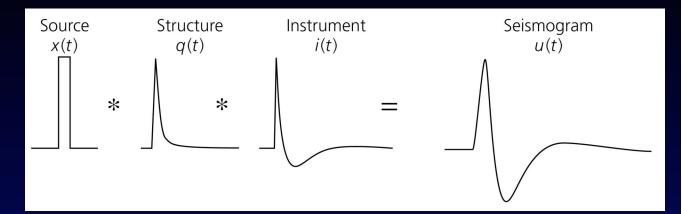
SYNTHETIC BODY WAVE SEISMOGRAM

Regard ground motion recorded on seismogram as a combination of factors:

- earthquake source

- earth structure through which the waves propagated

- seismometer

Create synthetic seismogram as Fourier domain convolution of these effects

$$u(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} U(\omega)e^{i\omega t}\, d\omega \qquad U(\omega) = \int_{-\infty}^{\infty} u(t)e^{-i\omega t}\, dt$$

$$s(t) = w(t) * r(t) = \int_{-\infty}^{\infty} w(t-\tau)r(\tau)d\tau$$

$$u(t) = x(t) * e(t) * q(t) * i(t)$$

$$U(\omega) = X(\omega)\, E(\omega)\, Q(\omega)\, I(\omega)$$

SOURCE TIME FUNCTION DURATION PROPORTIONAL TO FAULT LENGTH L AND THUS CONSTRAINS IT
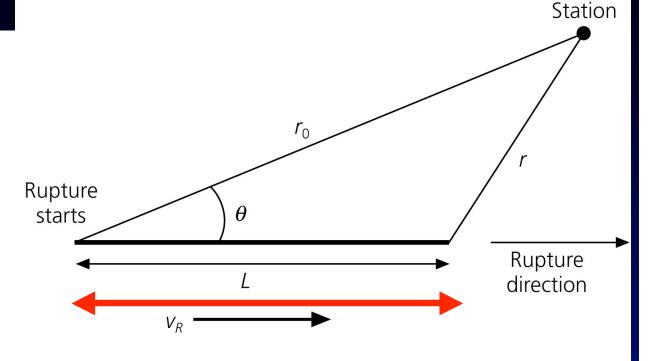
Source time function

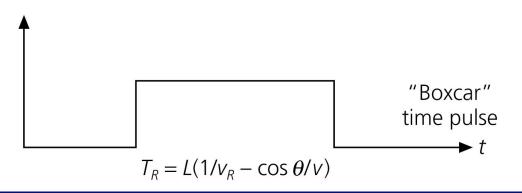V_R = rupture velocity

T_R = rupture time

$r^2 = r_o^2 + L^2 - 2r_o L \cos\theta$

$r \approx r_o - L \cos\theta$

$T_R = L \left(1/V_R - \cos\theta/V\right)$

$= (L/V)\left(V/V_R - \cos\theta\right)$

Station

r_0

r

Rupture starts

θ

L

Rupture direction

v_R

"Boxcar" time pulse

t

$T_R = L(1/v_R - \cos\theta/v)$

Also depends on seismic velocity V and rupture velocity Vr

V/V$_R$ Ratio
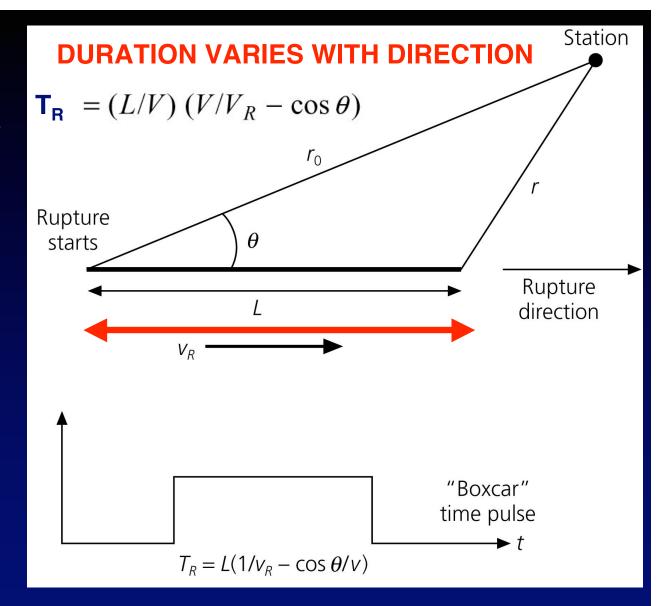
Wave velocity V

Rupture velocity V$_R$

Earthquake

Tsunami

Thunder and lightning

DURATION VARIES WITH DIRECTION

$$T_R = (L/V)(V/V_R - \cos\theta)$$

Station

Rupture starts

r_0

r

θ

L

v_R

Rupture direction
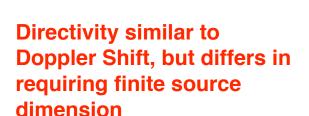
"Boxcar" time pulse

t

$$T_R = L(1/v_R - \cos\theta/v)$$

Figure 4.3-4: Effect of rupture directivity on the source time function.

Area = M_0

$\theta = 90°$

Area = M_0

$\theta = 180°$

Fault

Rupture direction

Area = M_0

$\theta = 0°$

Directivity similar to Doppler Shift, but differs in requiring finite source dimension
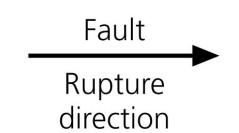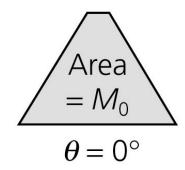
Area = M_0

$\theta = 270°$

Stein & Wysession, 2003

Analogous effect: thunder generated by sudden heating of air along a lightning channel in the atmosphere. Observers in positions perpendicular to the channel hear a brief, loud, thunder clap, whereas observers in the channel direction hear a prolonged rumble.

BODY WAVE MODELING FOR DEPTH DETERMINATION

Earthquake mechanism reasonably well constrained by first motions.

To check mechanism and estimate depth, synthetic seismograms computed for various depths.
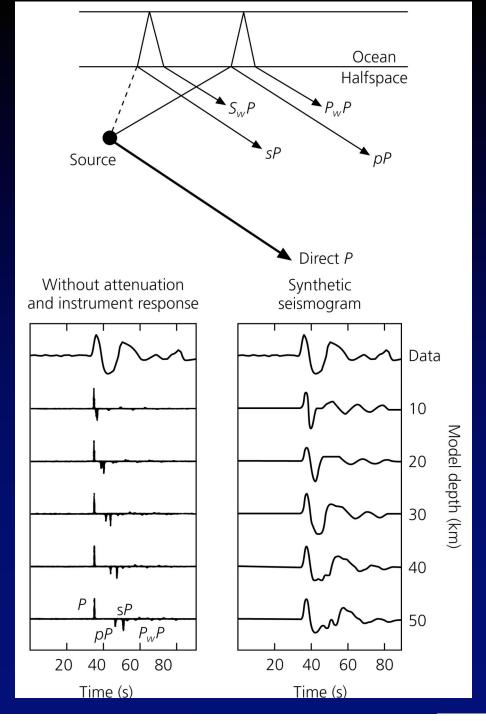
Data fit well by depth ~30 km.

Depths from body modeling often better than from location programs using arrival times

International Seismological Center gave depth of 0 ± 17 km: Modeling shows this is too shallow

Depth constrains thermomechanical structure of lithosphere

Stein and Wiens, 1986

Ocean
Halfspace

S_wP P_wP

sP pP

Source

Direct P

Without attenuation and instrument response   Synthetic seismogram

Data

10

20

30

40

50

Model depth (km)

P sP
pP P_wP

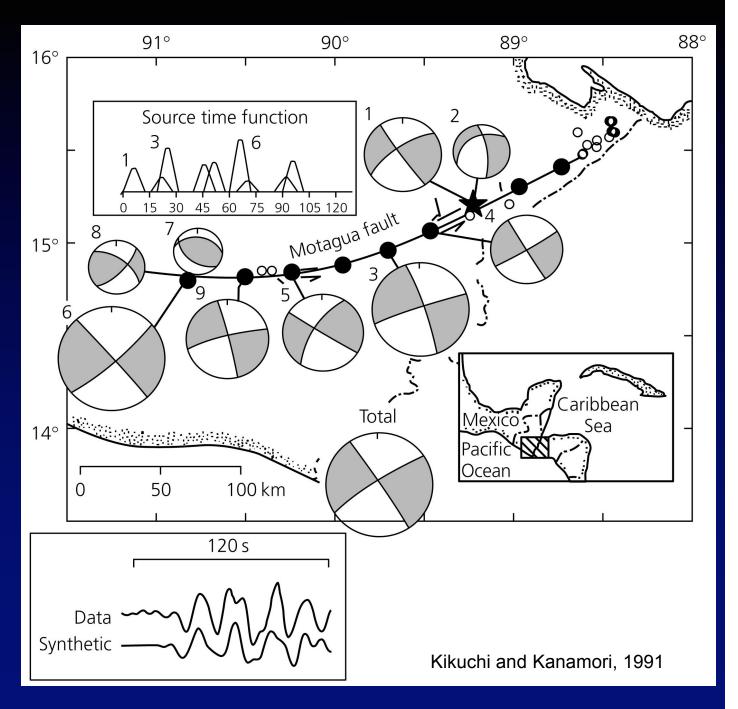20 40 60 80
Time (s)

20 40 60 80
Time (s)

MODEL COMPLEX EVENT BY SUMMING SUBEVENTS

1976 Guatemala Earthquake

Ms 7.5 on Motagua fault, transform segment of Caribbean- North American plate boundary

Caused enormous damage and 22,000 deaths

Source time function

Motagua fault

Mexico

Caribbean Sea

Pacific Ocean

Total

0   50   100 km

120 s

Data

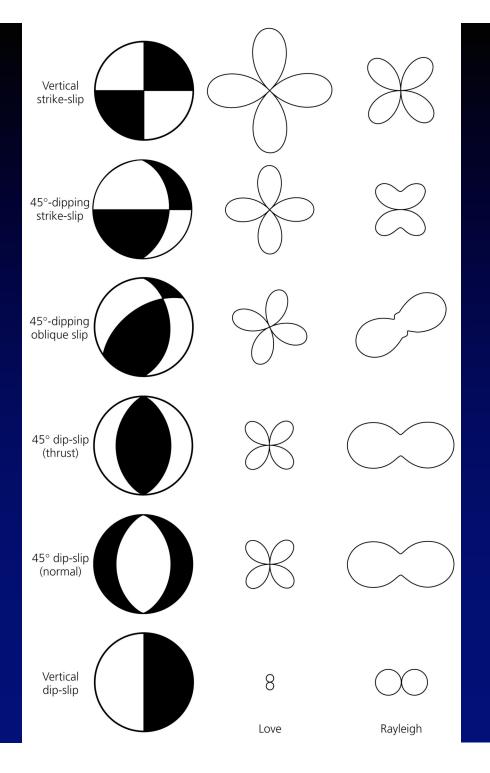Synthetic

Kikuchi and Kanamori, 1991

SURFACE WAVE AMPLITUDE RADIATION PATTERNS

Amplitude radiation patterns for Love and Rayleigh waves corresponding to several focal mechanisms, all with a fault plane striking North.

Show amplitude of surface waves in different directions

Can be generated for any fault geometry and compared to observations to find the best fitting source geometry

Stein & Wysession, 2003

Vertical strike-slip

45°-dipping strike-slip

45°-dipping oblique slip

45° dip-slip (thrust)

45° dip-slip (normal)

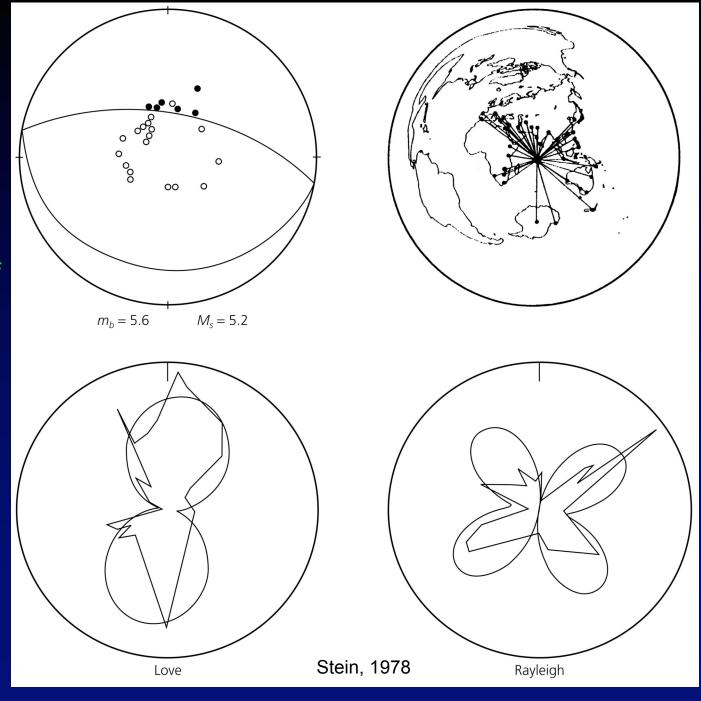Vertical dip-slip

Love

Rayleigh

SURFACE WAVE MECHANISM CONSTRAINT

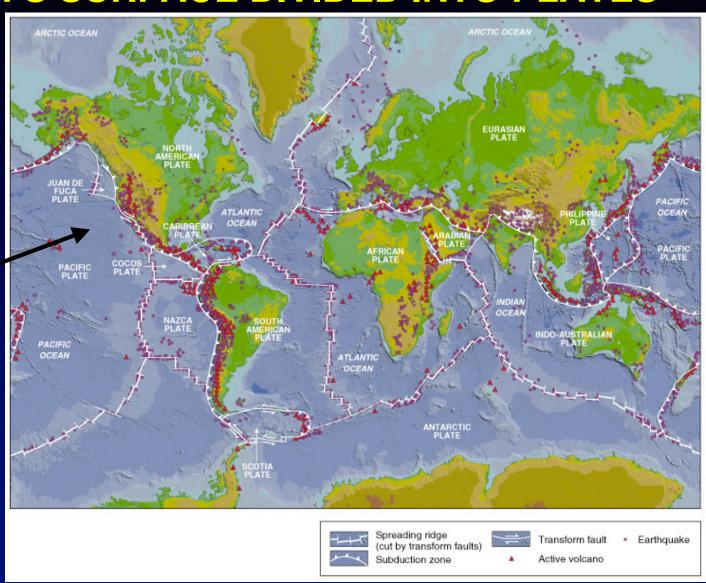Normal faulting earthquake in diffuse plate boundary zone of Indian Ocean

First motions constrain only E-W striking, north-dipping, nodal plane

Second plane derived by matching theoretical surface wave amplitude radiation patterns (smooth line) to equalized data.

$m_b = 5.6$ $M_s = 5.2$

Love

Stein, 1978

Rayleigh

EARTH'S SURFACE DIVIDED INTO PLATES

San Andreas fault: boundary between Pacific & North American plates
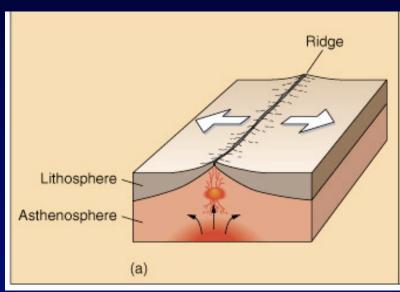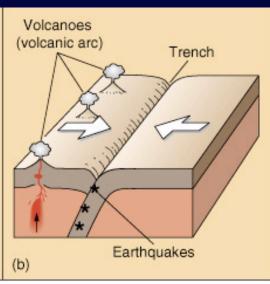
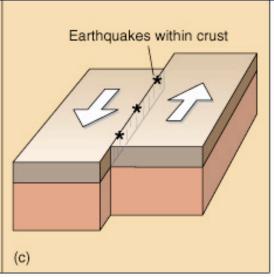# PLATES MOVE AT A FEW INCHES PER YEAR (AS FAST AS FINGERNAILS GROW)

RIDGE - NEW PLATE FORMS

SUBDUCTION - PLATE DESTROYED

TRANSFORM - PLATES SLIDE BY

(a) Ridge, Lithosphere, Asthenosphere

(b) Volcanoes (volcanic arc), Trench, Earthquakes

(c) Earthquakes within crust

DIFFERENT MOTIONS MAKE DIFFERENT BOUNDARIES

EXCITING THINGS - EARTHQUAKES & VOLCANOES HAPPEN AT THEIR BOUNDARIES
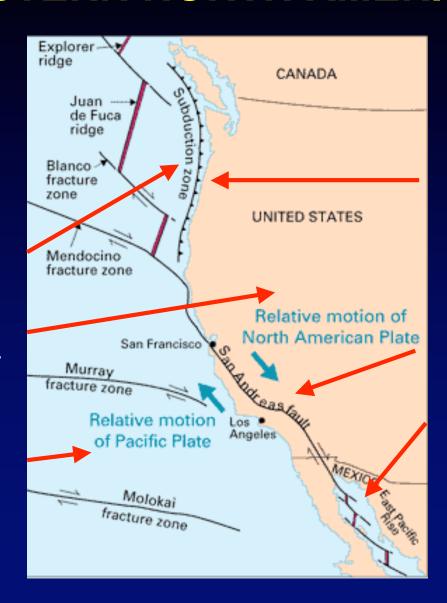
WESTERN NORTH AMERICA

Three Plates:

Juan de Fuca

North America

Pacific

Three Boundaries:
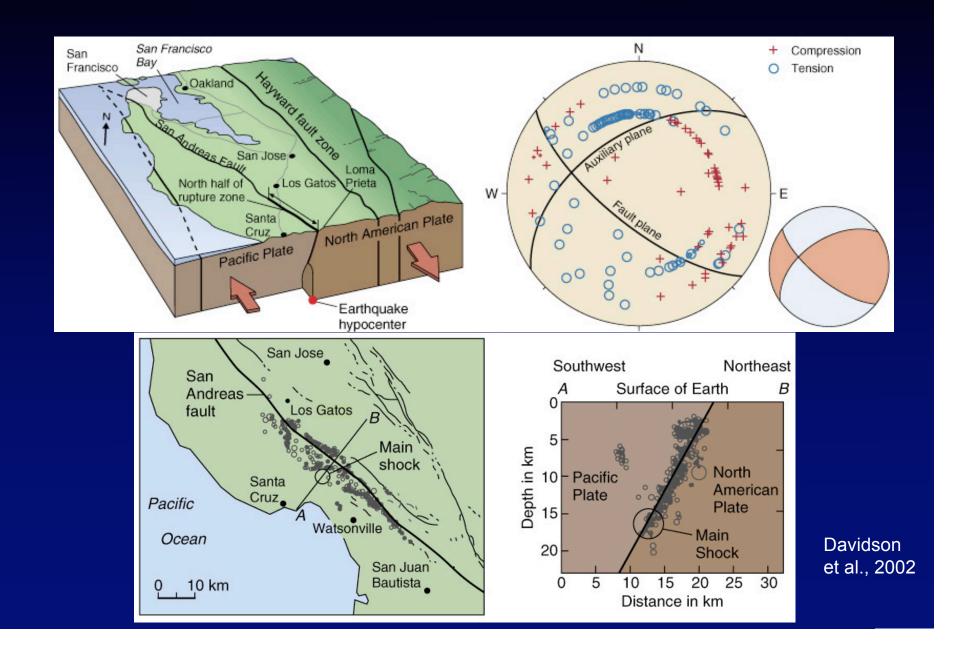
Cascadia subduction zone

San Andreas transform

Gulf of California spreading center

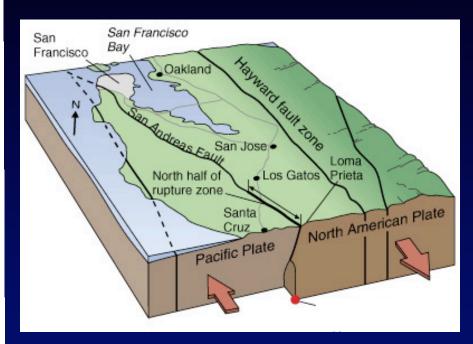# SAN ANDREAS FAULT NEAR SAN FRANCISCO

Type example of transform on land

Loma Prieta 1989 Ms 7.1

Davidson et al., 2002

Distributed motion between North American & Pacific Plates
Most on San Andreas: some on other faults

San Francisco area - SAF broke in 1906: M 7.9

Hayward fault broke in 1868: M 7

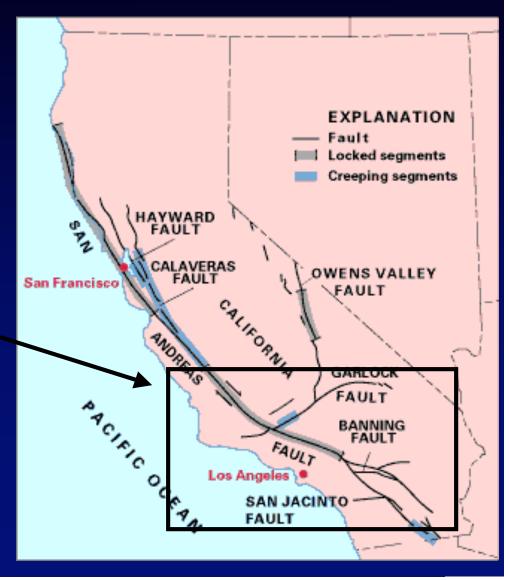# Distributed motion between North American & Pacific Plates
Most on San Andreas: some on other faults

Los Angeles area - SAF broke in 1857: M 7.9

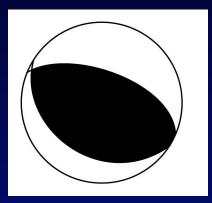**Smaller but damaging earthquakes on other faults**

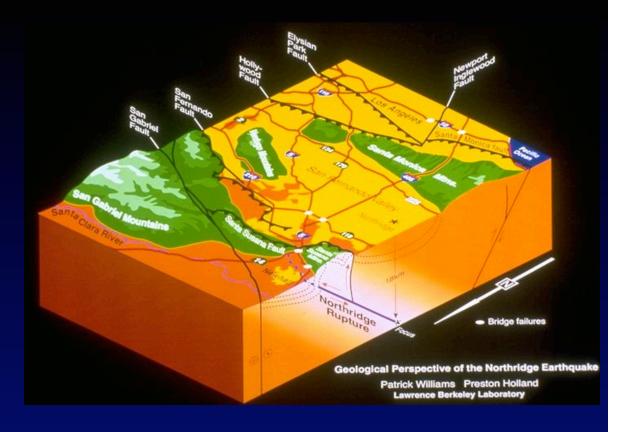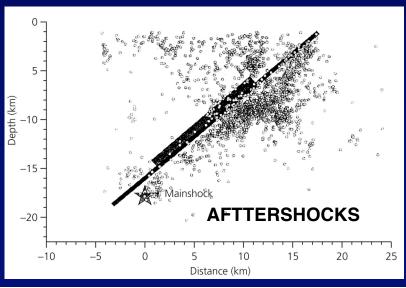1994 Northridge   M 6.7
58 deaths, $20B damage

Los Angeles Basin

Thrust earthquakes indicate shortening

1994 Northridge Ms 6.7

Geological Perspective of the Northridge Earthquake
Patrick Williams   Preston Holland
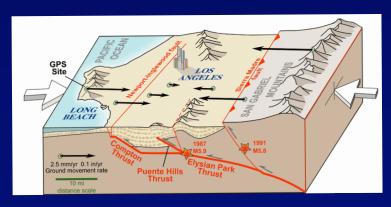Lawrence Berkeley Laboratory

AFTERSHOCKS

Caused some of the highest ground accelerations ever recorded. It illustrates that even a moderate magnitude earthquake can do considerable damage in a populated area. Although the loss of life (58 deaths) was small due to earthquake-resistant construction the $20B damage makes it the most costly earthquake to date in the U.S.
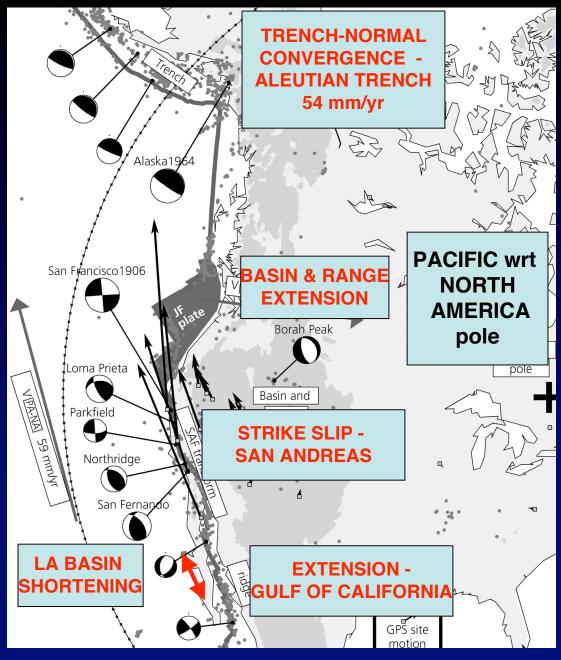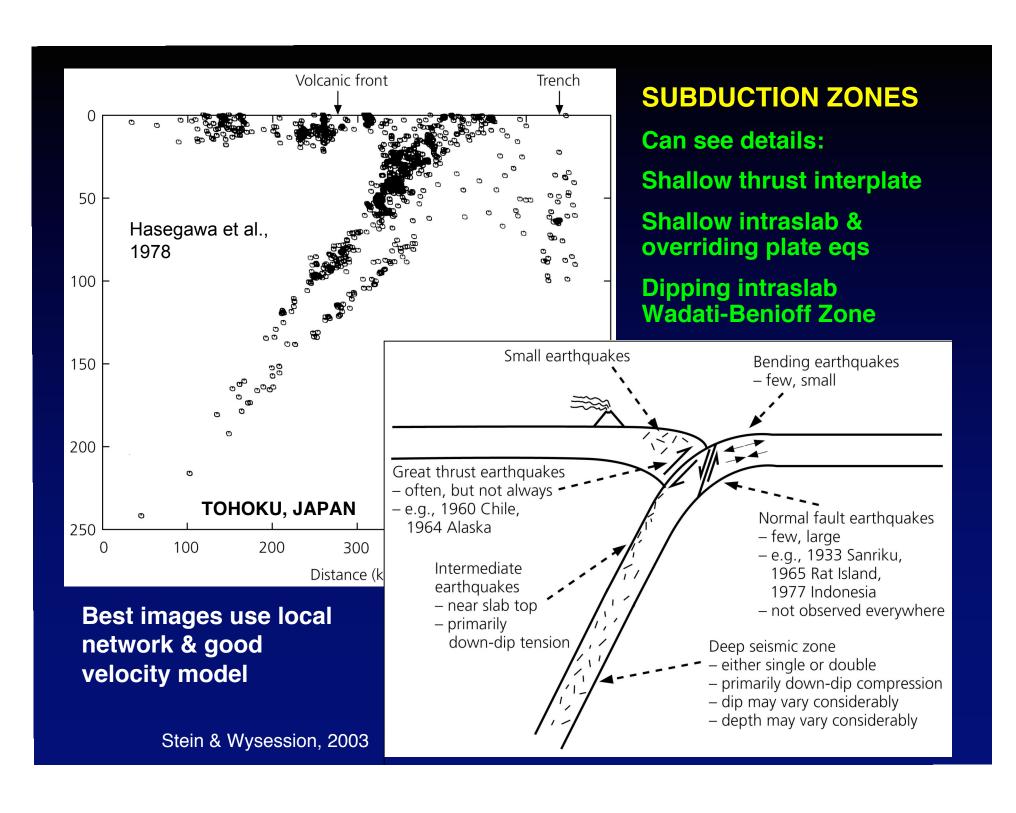
MECHANISMS SHOW BOTH NOMINAL PLATE BOUNDARY

Aleutian Trench: thrust
San Andreas: strike slip
Gulf of California: normal & strike slip

AND OTHER BOUNDARY ZONE DEFORMATION

Basin & Range: normal
Los Angeles Basin: thrust

TRENCH-NORMAL CONVERGENCE - ALEUTIAN TRENCH 54 mm/yr

Trench

Alaska1964

PACIFIC wrt NORTH AMERICA pole

BASIN & RANGE EXTENSION

San Francisco1906

JF plate

Borah Peak

Loma Prieta

Basin and

Parkfield

STRIKE SLIP - SAN ANDREAS

Northridge

V PA-NA 59 mm/yr

SAF transform

San Fernando

LA BASIN SHORTENING

EXTENSION - GULF OF CALIFORNIA

ridge

GPS site motion

pole

Bawden et al., 2001

Stein & Wysession, 2003

SUBDUCTION ZONES

Can see details:

Shallow thrust interplate

Shallow intraslab & overriding plate eqs

Dipping intraslab Wadati-Benioff Zone

Volcanic front

Trench

Hasegawa et al., 1978

TOHOKU, JAPAN

Distance (k

Best images use local network & good velocity model

Stein & Wysession, 2003

Small earthquakes

Bending earthquakes – few, small

Great thrust earthquakes
– often, but not always
– e.g., 1960 Chile,
   1964 Alaska

Intermediate earthquakes
– near slab top
– primarily
   down-dip tension

Normal fault earthquakes
– few, large
– e.g., 1933 Sanriku,
   1965 Rat Island,
   1977 Indonesia
– not observed everywhere

Deep seismic zone
– either single or double
– primarily down-dip compression
– dip may vary considerably
– depth may vary considerably

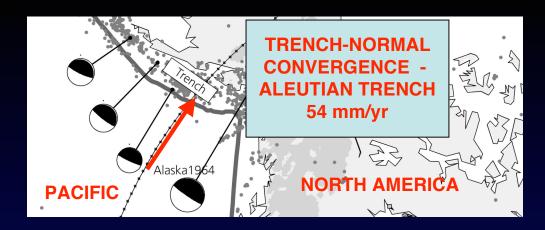# 1964 ALASKA EARTHQUAKE
M_s 8.4 M_w 9.1

Pacific subduction beneath North America

~ 7 m of slip on 500x300 km^2 of Aleutian Trench

Second largest earthquake recorded to date

~ 130 deaths

Catalyzed idea that great thrust fault earthquakes result from slip on subduction zone plate interface

TRENCH-NORMAL CONVERGENCE - ALEUTIAN TRENCH
54 mm/yr

PACIFIC

NORTH AMERICA

Trench

Alaska1964

PLAY

JUAN DE FUCA PLATE SUBDUCTING BENEATH NORTH AMERICA

2001 Nisqually earthquake
($2B damage)
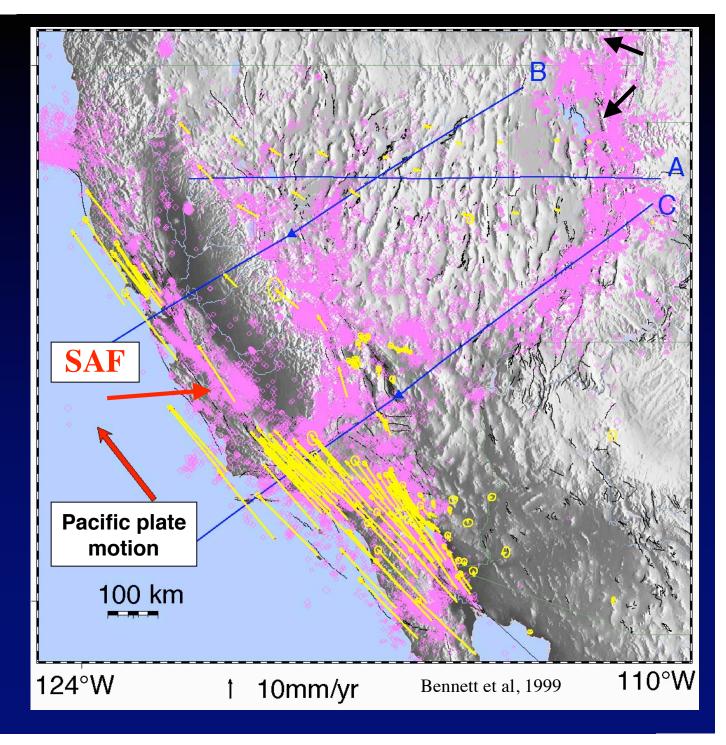
Mt Saint Helens 1980 eruption
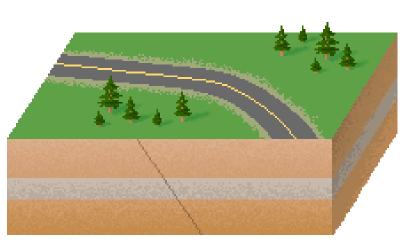(57 deaths;
$2B damage)

SOME PACIFIC - NORTH AMERICA MOTION SPREAD AS FAR EAST AS UTAH & MONTANA

GPS site motions relative to North America - and earthquakes - show broad boundary zone

SAF

Pacific plate motion

100 km

124°W   ↑   10mm/yr   Bennett et al, 1999   110°W

B
A
C

Wasatch fault, Salt Lake City, Utah

Hebgen Lake, Montana
1959 M 7.5
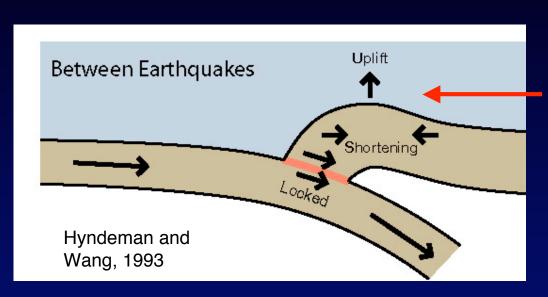
Molnar & Tapponnier, 1977
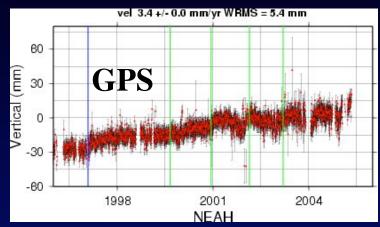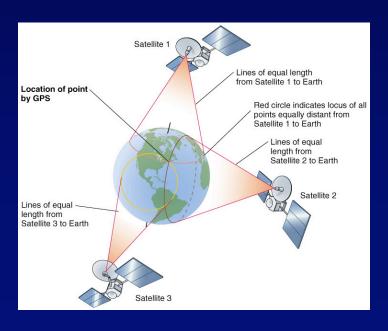
TSUNAMI GENERATION I: OVERRIDING PLATE FLEXED BETWEEN MAJOR EARTHQUAKES

Hyndeman and
Wang, 1993
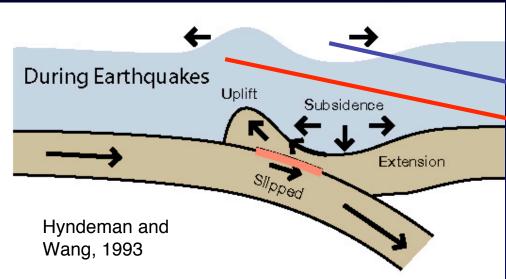
Indian plate subducts beneath Burma microplate
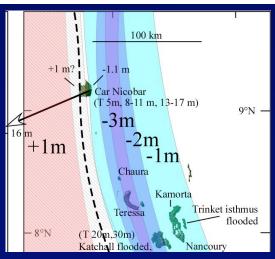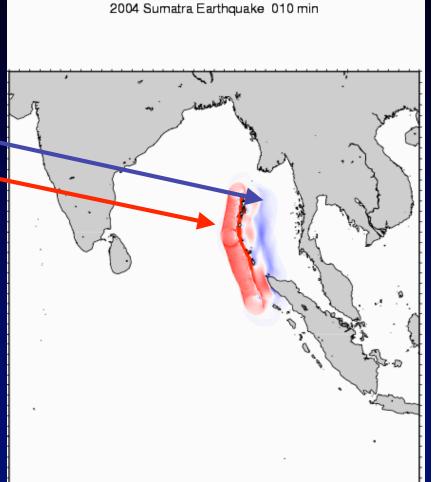
TSUNAMI GENERATION II: SEAFLOOR REBOUNDS DURING EARTHQUAKE

During Earthquakes

Uplift   Subsidence

Slipped   Extension

Hyndeman and Wang, 1993

2004 Sumatra Earthquake 010 min

Islands went up & down

R. Bilham

100 km

+1 m?   -1.1 m
Car Nicobar
(T 5m, 8-11 m, 13-17 m)
9°N
16 m
-3m
+1m   -2m
-1m
Chaura
Kamorta
Teressa   Trinket isthmus
flooded
8°N   (T 20m,30m)
Katchall flooded,   Nancoury

Water motion:
Red - up, blue down
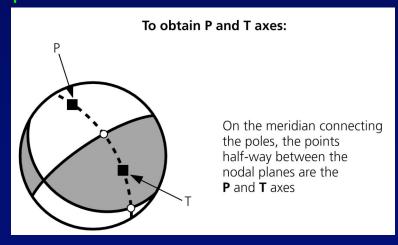
INFER STRESS ORIENTATIONS FROM FOCAL MECHANISMS

Simple model predicts faulting on planes 45° from maximum and minimum compressive stresses
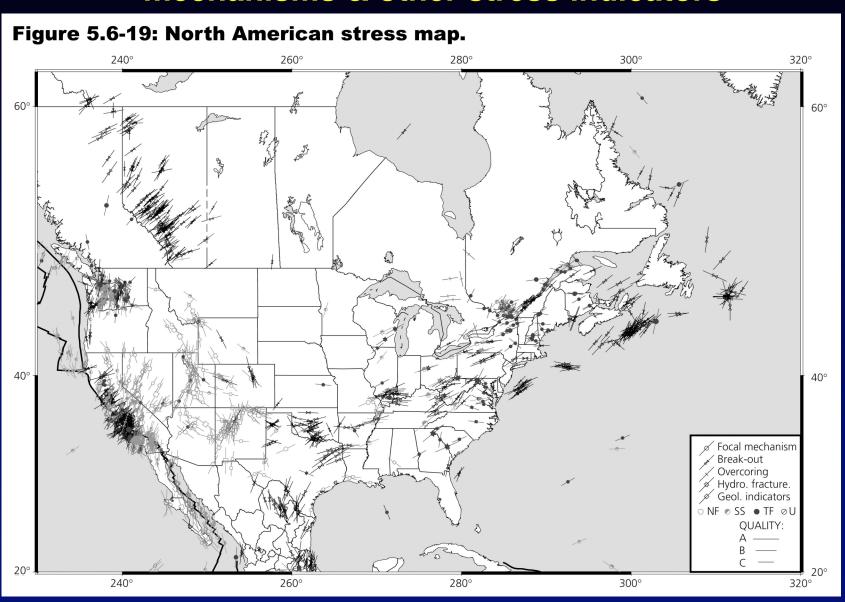
These stress directions are halfway between nodal planes

Most compressive (P) and least compressive stress (T) axes can be found by bisecting the dilatational and compressional quadrants

To obtain P and T axes:

On the meridian connecting the poles, the points half-way between the nodal planes are the **P** and **T** axes

Stein & Wysession, 2003

WORLD STRESS MAP   Combines earthquake mechanisms & other stress indicators

Figure 5.6-19: North American stress map.

SUMMARY

Earthquake locations and focal mechanisms can give crucial insight into regional tectonics

Integration with plate motion, geologic, and geodetic data is very powerful